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A PRELIMINARY STUDY OF THE APPLICATION OF PROBABILISTIC RISK ASSESSMENT TECHNIQUES TO HIGH-ENERGY LASER SAFETY

Peter Smith
Ken Keppler

TASC, Inc.
4241 Woodcock Drive Ste. B-100
San Antonio, TX 78228

David Van Veldhuizen

HUMAN EFFECTIVENESS DIRECTORATE
DIRECTED ENERGY BIOEFFECTS DIVISION
OPTICAL RADIATION BRANCH
8111 18th Street
Brooks AFB, Texas 78235-5215

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This technical report has been reviewed and is approved for publication.

CECILIA MONTES DE OCA, 1st Lt, USAF
Contract Monitor

RICHARD L. MILLER, PhD
Chief, Directed Energy Bioeffects Division

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ABSTRACT

A deterministic approach to laser hazard assessment is used in most laser safety standards. Personnel are protected from hazardous laser radiation by defining a space within which the direct, reflected, or scattered radiation during laser operation exceeds the safe Maximum Permissible Exposure level. Controlling access to this space insures safety. Although this approach has satisfied the commercial and industrial laser communities for many years, it may not be applicable to the high-power (up to megawatt) laser systems currently being developed by the US military. These systems will have extremely long laser hazard distances, and controlling access to this space will be unrealistic, especially when the likelihood of hazardous human exposure is low. For these situations, an alternative analytical approach that estimates both the level of risk and the degree of risk reduction achievable by controlling key contributors can be applied. Analytic risk assessment tools are finding increasing application in a wide variety of hazard assessments, in both industrial and commercial situations. These tools use scientific data, assumptions, and mathematical models to estimate the likelihood, frequency, and severity of harm to people exposed to the hazard. This report discusses the application of such tools to laser safety and considers the uncertainties associated with probability density functions applied to key factors such as atmospheric scintillation, reflected radiation, population distribution and ocular injury.

1 INTRODUCTION

The Department of Defense has several active High-Energy Laser (HEL) weapons programs with the potential to mature in the not too distant future. These programs include the Airborne Laser (ABL), the Tactical High Energy Laser (THEL), the Space Based Laser (SBL), Free Electron Laser (FEL), and the Airborne Tactical Laser (ATL). These high-power (up to megawatt) systems will require field-testing and training prior to operational deployment. They will all have extremely long eye hazard distances for both the direct beam and reflected radiation[1], and will, initially, require testing within the limited space of test ranges.

For outdoor operations Air Force laser hazard assessment techniques[2,3] are based on the American National Standard.[4] The principal way that personnel are protected is by defining a space within which the direct, reflected, or scattered radiation during laser operation exceeds the Maximum Permissible Exposure (MPE[a]). This space is known as the Nominal Hazard Zone (NHZ), and controlling access to it insures safety. The ANSI approach has satisfied the commercial and industrial laser communities for many years,

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[a] The MPE is defined as the level of laser radiation to which a person may be exposed without hazardous effect or adverse biological changes in the eye or skin.

and a testament to the level of protection it provides is the relatively low number of laser accidents in comparison to the number of lasers now in use. Indeed, where there have been injuries, these have invariably occurred when the safety standards have not been complied with, usually a failure to wear the required protective eyewear.[5]

Military laser scenarios (testing, training), often involve the use of Class 4 lasers out-of-doors. These lasers have long hazard distances for the direct beam, and consequently hazard zones can be extremely large[6,7], even though the actual likelihood of hazardous human exposure is low. These distances and zones will be proportionally greater for high-energy laser systems, and deterministic hazard analysis will produce hazard zones that are unacceptably large due the level of conservatism applied. Thus, for these situations an alternative analytical approach that estimates both the level of risk, and the degree of risk reduction achievable by controlling key contributors can be considered.[8]

One approach that is used extensively by the United Kingdom Ministry of Defence (UK MOD), is the technique of probabilistic risk assessment (PRA). The UK MOD has applied PRA to laser hazard evaluation to support testing and training with airborne laser range finders since 1976.[8-10] Such a requirement for military laser systems has not previously been necessary in the US, mainly because ranges are significantly larger, enabling the NHZ to be kept within the range boundary. However, analytic risk assessment tools are finding increasing application elsewhere in the US in a wide variety of other hazard assessments in both industrial and commercial applications. Indeed, the approach is presented in several recent US science and policy discussion documents[11-13], and is used to support missile tests and space launches.[14,15]

These tools use scientific data, assumptions and mathematical models to estimate the likelihood, frequency and severity of harm to people or natural resources exposed to a hazard. The application of these tools to public health, safety, and environmental problems has become commonplace in the peer-reviewed scientific and medical literatures. Legislation that would have mandated quantitative risk assessment for all federal environmental, health, and safety regulations came close to being passed several times in the 1990s: SB110 in 1992, HR9 in 1994, the Johnston-Robb Bill in 1996, and S746 in 1999.[16] In addition, the US Environmental Protection Agency (EPA) has recently published its policy for use of probabilistic analysis in risk assessment.[13]

The application of the current deterministic NHZ approach to the next generation of high-energy lasers will restrict severely the opportunities for training, and the operation of these devices, even though the likelihood for a hazardous event may be small. It may even be that realistic training would be precluded. In addition, the dynamic, three dimensional nature of the scenarios, with the potential for a fast moving laser source and target, coupled with the potential for reflected radiation to be scattered over large areas, mean that the hazard analysis will be particularly complex and require extensive computational techniques. The dynamic nature of a high-energy laser air-to-air missile engagement means that an easy "cookbook" certification of the range will not be appropriate. The requirement for a realistic assessment of the risk using quantitative techniques will therefore be inevitable.

Advancing to probabilistic techniques will allow for a quantitative analysis of uncertainty and variability, and present the risk manager with ranges of risk instead of a high-end, single-point, risk estimate. By showing the distribution of health risk, a more realistic picture of the actual risk posed to potential receptors will be provided. It is not the intent to recommend that a probabilistic analysis be conducted for all USAF laser hazard evaluations. Such analysis should be a part of a tiered approach to risk assessment that progresses from simpler methodologies (e.g., deterministic) on to more complex (e.g., probabilistic) analyses as the risk management situation demands. A key benefit of the application of probabilistic risk assessment, when used, is that it is more informative, and can provide additional relevant information on which to base risk management decisions.

Risk[b] - Assessment and Management

1.1 General Principles

It is useful to begin by drawing a distinction between the terms **risk assessment** and **risk management**. A useful clarification is given by the explanation that risk assessment answers the question *"How risky is the situation?"* whereas risk management answers the question *"What shall we do about it?"*

Risk management is the process of identifying, evaluating, selecting, and implementing actions to reduce risk to human health and to ecosystems. The goal of risk management is scientifically sound, cost-effective, integrated actions that reduce or prevent risks while taking into account social, cultural, ethical, political, and legal considerations. Risk management is a systematic and logical process to identify and control hazards. This process includes any or all of the following steps: 1) identify the hazards, 2) define hazard levels, 3) define risks, 4) define and implement risk reduction measures, 5) obtain approval from proper authority, and, 6) ultimately accept the hazard or risk. The AF has implemented these principles in Range Safety standards, most notably those for inert debris[15], and at the Eastern and Western ranges.[17]

Risk assessment is defined as the objective process that analyzes the form, dimension, and characteristics of the risk. It is primarily a scientific effort in which data from appropriate sources are used to estimate the nature and probability of risk at a given location. Risk management on the other hand is the process by which decisions (subjective policy, cost-benefit analysis, and value judgment) are made using all available information. A risk assessment is, nevertheless, an integral part of the risk management process, and provides important feedback to the research process (Figure 1).[18]

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[b]Risk is defined as the probability that a substance or situation will produce harm under specified conditions[11]. Risk is a combination of two factors: the probability that an adverse event will occur (such as a specific disease or type of injury), and, the consequences of the adverse event. Risk encompasses impacts on public health and on the environment, and arises from exposure and hazard. Risk does not exist if exposure to a harmful substance or situation does not or will not occur. Hazard is determined by whether a particular substance or situation has the potential to cause harmful effects.

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A risk assessment is an evaluation of the potential heath effects on individuals or populations exposed to hazardous materials or situations. It should be based on scientific information and public health policy considerations and must consider all relevant, reliable, and reasonably available information, and must explain the basis for selecting the information relied upon. Any significant assumptions must be identified along with their basis in science or policy. An explanation of the basis for the choice of any combination of assumptions should also be given, together with the extent to which the assumption has been validated by, or conflicts with, empirical data. The risk assessment should also describe reasonable alternative assumptions that were considered but not selected.

The risk assessment shall include, where appropriate, descriptions of:

i. the hazard;
ii. the populations or natural resources that are the subject of the risk assessment;
iii. exposure scenarios, including estimates of the population or natural resources at risk and the likelihood of such scenarios;
iv. the nature and severity of the harm from exposure to the hazard; and,
v. the major uncertainties in each component of the risk assessment and their impact on the assessment's outcome.

The risk assessment should provide information on the risk to a single person (individual risk) and the total risk to an exposed population (collective risk). Collective risk is usually specified as either a value per mission or per year.
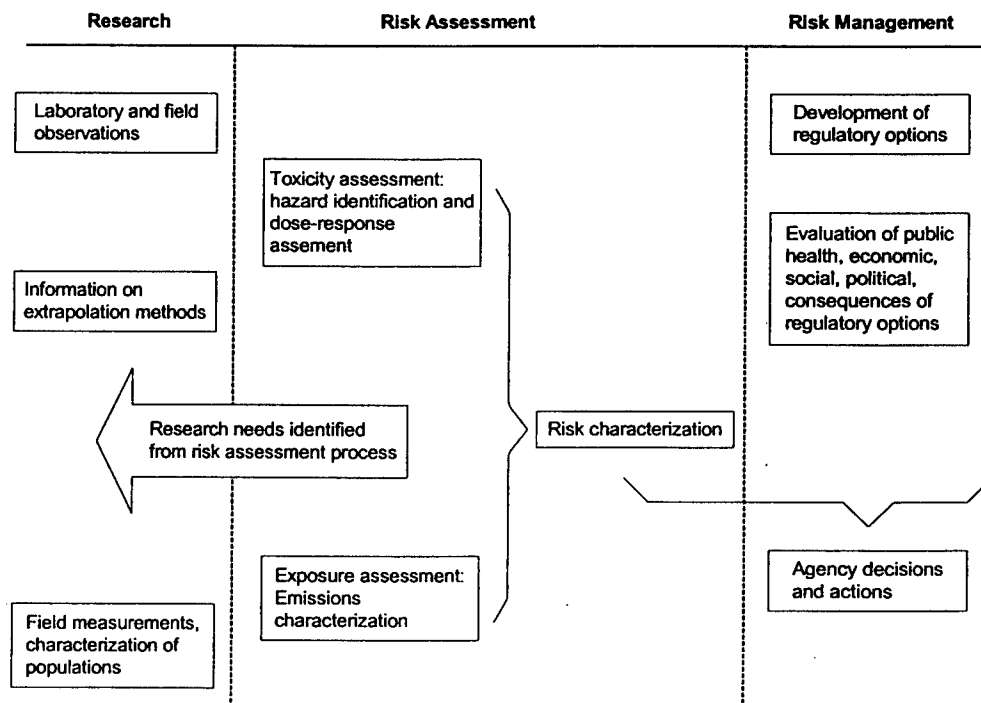

Figure 1. Elements of risk assessement and risk management

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If it is determined that an unacceptable risk exists then the risk assessment can inform the risk management process and be used to target areas for risk reduction and mitigation. The use of risk assessment in this way, as a tool in decision making, has been a key component in the Air Force's Installation Restoration Program since the program's inception in 1984.[19] The Program has been guided by the Environmental Protection Agency's (EPA) policy on the use of probabilistic risk assessment.[20]

1.2 EPA Approach

When risk assessments using probabilistic analysis techniques are submitted to the EPA for review and evaluation, they require eight specific conditions to be satisfied to ensure high quality and science. While these conditions may not be specifically required for a high-energy laser probabilistic risk assessment, it would be prudent to use them as guidance, considering them in detail, and following their example. The eight EPA conditions are:

1. The purpose and scope of the assessment should be clearly articulated in a "problem formulation" section that includes a full discussion of any highly exposed or highly susceptible sub-populations evaluated (e.g., children, the elderly). The questions the assessment attempts to answer are to be discussed and the assessment endpoints are to be well defined.

2. The methods used for the analysis (including all models used, all data upon which the assessment is based, and all assumptions that have a significant impact upon the results) are to be documented and easily located in the report. This documentation is to include a discussion of the degree to which the data used are representative of the population under study. Also, this documentation is to include the names of the models and software used to generate the analysis. Sufficient information is to be provided to allow the results of the analysis to be independently reproduced.

3. The results of sensitivity analyses are to be presented and discussed in the report. Probabilistic techniques should be applied to the compounds, pathways, and factors of importance to the assessment, as determined by sensitivity analyses or other basic requirements of the assessment.

4. The presence or absence of moderate to strong correlation or dependencies between the input variables is to be discussed and accounted for in the analysis, along with the effects these have on the output distribution.

5. Information for each input and output distribution is to be provided in the report. This includes tabular and graphical representations of the distributions (e.g., probability density function and cumulative distribution function plots) that indicate the location of any point estimates of interest (e.g., mean, median, 95th percentile). The selection of distributions is to be explained and justified. For both the input and output distributions, variability and uncertainty are to be differentiated where possible.

6. The numerical stability of the central tendency and the higher end (i.e., tail) of the output distributions are to be presented and discussed.

7. Calculations of exposures and risks using deterministic (e.g., point estimate) methods are to be reported if possible. Providing these values will allow comparisons between the probabilistic analysis and past or screening level risk assessments. Further, deterministic estimates may be used to answer scenario specific questions and to facilitate risk communication. When comparisons are made, it is important to explain the similarities and differences in the underlying data, assumptions, and models.

8. Since fixed exposure assumptions (e.g., exposure duration, body weight) are sometimes embedded in the toxicity metrics (e.g., Reference Doses, Reference Concentrations, unit cancer risk factors), the exposure estimates from the probabilistic output distribution are to be aligned with the toxicity metric.

Risk modeling is invariably necessary because the acceptable risk levels are not measurable, and direct sampling of the exposure is not feasible. Nevertheless, the risk assessment must demonstrate a decisional process of diligent data collection and revelation, careful identification of significant facets of the problem, and consideration of possible alternative solutions, and lucid explanation of its assumptions, conclusions and judgments.

1.3 Characterization of Variability and Uncertainty

Where deterministic risk assessment uses high-end point estimates for input values, probabilistic risk assessment uses distributions, and this enables a quantitative analysis of the variability and uncertainty of the risk for the population. Variability refers to true heterogeneity in characteristics with a population, and cannot be reduced by taking more samples. Uncertainty, on the other hand, refers to lack of knowledge and can be reduced, in theory, by further data collection. In practice, cost, time and ethical constraints, together with a minimal impact on the outcome of the assessment, often make additional data collection impractical. Separating variability and uncertainty during the analysis can be necessary to identify parameters where additional data are needed.

The importance of adequately characterizing variability and uncertainty in risk assessments has been emphasized by the EPA, which has issued guidance on the appropriate use of an application for analyzing variability and uncertainty in risk assessments.[13] While this guidance relates specifically to the use of Monte Carlo analysis, the EPA recognizes that Monte Carlo analysis is not the only acceptable approach for risk assessments.

One of the most important challenges facing the risk assessor is to communicate effectively the insights that an analysis of variability provides. It may be important to remember that the insights may be qualitative in nature (e.g. "a greater risk being involved in a fatal road accident") even though they may be quantitatively based (e.g. "a risk of 1 in 1,000,000").

2 SCENARIO DEFINITION

The process of constructing and solving problems for both deterministic hazard analysis and probabilistic risk assessments can be viewed as two broad types of activity. The first is building a useful mental picture, or model, of the activity and the second is getting reasonable values into a model. The intention in this report is for Section 2 and Section 3 respectively to deal with these broad issues in a broad sense.

The way in which probabilistic risk assessment techniques might be utilized for a high-energy laser scenario will depend to a great extent on the specific application. The use of an airborne high-energy laser system against a fast moving airborne target represents the most challenging scenario for a HEL probabilistic risk assessment by virtue of the high relative motion of the source and target, long atmospheric paths, and potentially significant spread of reflected radiation, which varies rapidly with time. This scenario is also highly representative of a HEL engagement[1] and so it is appropriate to use it to provide an example for the application of probabilistic risk assessment to HEL safety.

2.1 Exposure Pathways

The first stage in the risk assessment is to define the routes that might lead to hazardous exposure. This involves identifying the potential pathways from the exit aperture of the laser, to the entrance aperture of the system at risk. For the purposes of this study, the system at risk will be the human eye, but it could be the skin, or a valuable asset such as another aircraft, or a satellite system. Typical questions that might be asked in this stage, for both a deterministic analysis and a probabilistic risk assessment, are given in Figure 2.

In the case of a deterministic hazard analysis, the answers to these questions are usually provided by worst-case values for each of the parameters. For example, worst-case estimates used for the laser output parameters may be maximum beam power, lowest beam divergence, and an upper bounded estimate of pointing accuracy (aiming errors). To allow for any local increases in beam irradiance due to atmospheric scintillation (see later), a worst-case gain value of 2.56 is often applied.[21] Reflections from the target would also be assumed to take on upper bound estimates. Finally, by definition, an unacceptable hazard exists when an uncontrolled location, e.g. outside the range boundary, is exposed to laser radiation in excess of the MPE, despite the fact that MPE values are set at least an order of magnitude lower than the thresholds for biological damage.[22]

For a probabilistic assessment there is an immediate requirement for a more detailed analysis of the key routes to human exposure, and an analysis of the variability and uncertainties associated with these pathways. The EPA guidelines[20] recommend restricting the use of probabilistic assessment to significant pathways and parameters, and, although specifying distributions for all or most variables is useful for exploring the full range of variability and uncertainty it is often unnecessary and not cost effective. The assessment can include a mixture of point estimates and distributions for the input

parameters to the exposure model. However, these point estimates should be continually reviewed to avoid the perception that they are constant and not subject to change. Using the schematic pathway illustrated in Figure 2, the following elements require further consideration.
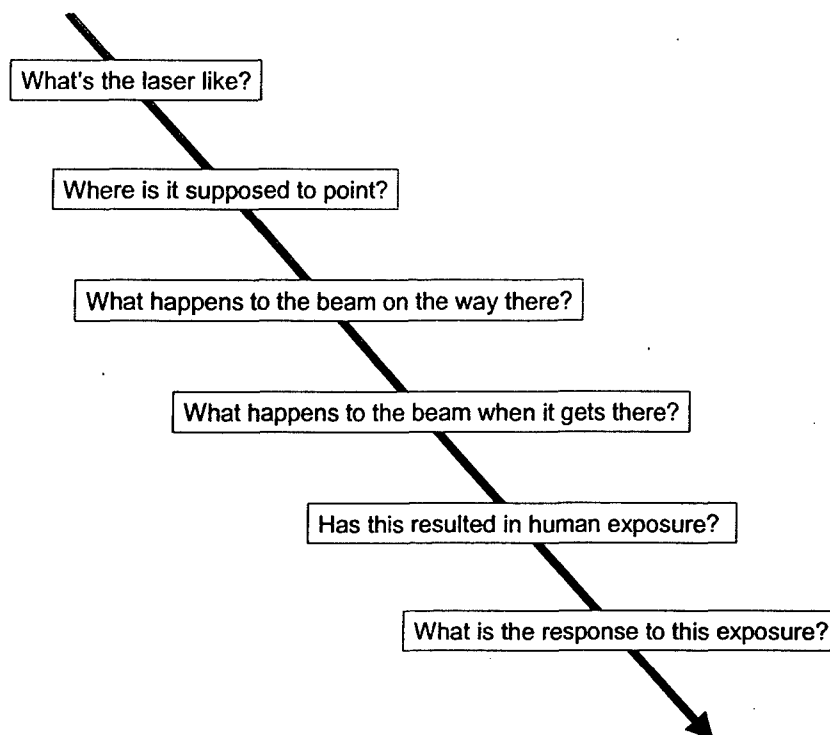
What's the laser like?

Where is it supposed to point?

What happens to the beam on the way there?

What happens to the beam when it gets there?

Has this resulted in human exposure?

What is the response to this exposure?

Figure 2. Key questions

2.1.1 Laser Characteristics

When manufacturers provide specifications for laser systems they often provide lower bound estimates for power/energy on the basis that if the system emits more power/energy then the customer asked for, then he is getting a little bit extra for his money. However, when calculating a hazard distances, the lower estimate would provide a correspondingly short hazard distance, and potentially underestimate the hazard. In addition, a laser beam is not homogenous in cross-section. Generally, the intensity falls off as a function of distance from the center of the beam, but there can be areas in the beam in which the irradiance is much greater than the average across the beam. The irradiance in these hot spots, as they are so called, can be two orders of magnitude greater than the average irradiance. The hot spots can be caused by inhomogeneities in the laser cavity and mirrors, or certain atmospheric conditions (see Section 2.1.3).

2.1.2 Aiming Parameters

The likelihood that the laser points in desired direction will depend on the characteristics of the laser tracking system operation. Different tracking systems will have differing levels of automatic or manual control, and hence accuracy, of the laser

sight line, and also present differing hazards to the observer when control of the sight line is lost for any particular reason. The definition of a suitable expression for the aiming accuracy will likely vary for each system under consideration. The more complex the tracking system, the more extensive will be the system hazard analysis to identify all the salient characteristics for consideration. Usual parameters would be the bore-sighing error and tracking error (jitter). The assessment of the laser sight line control system should consider both fault-free operation and behavior following a directional control system failure, along with any concurrent safety engineering systems (e.g. automatic shutdown in the event of a control system error).

2.1.3 Atmospheric Effects

In general, for any representative engagement scenario, there will be two principal laser beam paths that will need consideration in the context of laser propagation and atmospheric effects. The first will be the path of the direct beam from the laser source to the target. The second path will be that of any reflected radiation from the target to the ground (Figure 3). Whether these paths are air-to-air, air-to-ground, ground-to-air, or ground-to-ground will depend upon the particular engagement and any combination may be possible, e.g. the path from direct to reflected radiation may be air-air-ground, ground-air-ground, or one of a number of other combinations depending on the particular scenario under consideration.
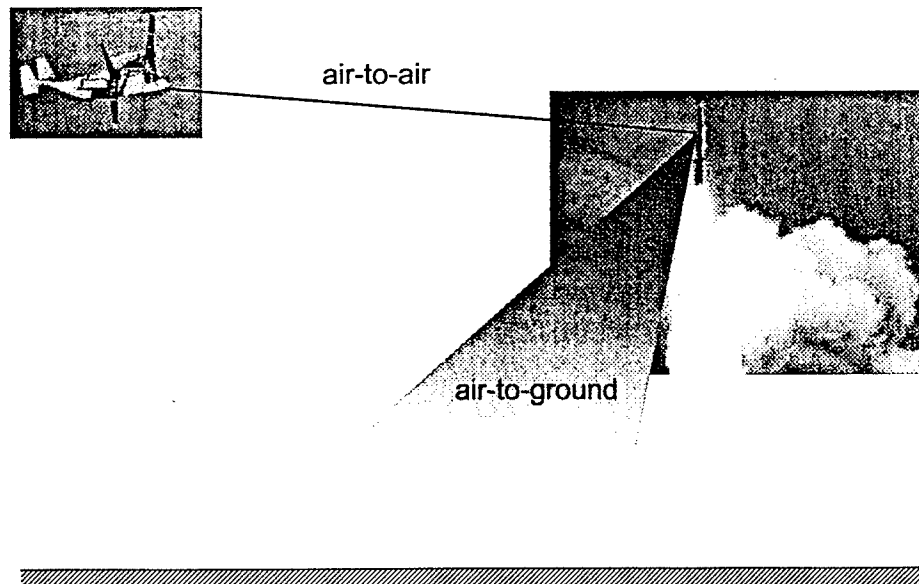

air-to-air

air-to-ground

Figure 3. Hypothetical scenario

Regardless of the scenario, a laser beam will be subject to two main atmospheric effects along its path, namely atmospheric attenuation and atmospheric turbulence leading to scintillation.

2.1.3.1 Atmospheric Attenuation (extinction)

Over long beams paths, atmospheric attenuation may result in significant losses. The attenuation, which varies with the laser wavelength, is due to large particle scattering, molecular scattering and absorption by gas molecules. Large particle, or Mie, scattering is the dominant mechanism in the visible and near infrared part of the spectrum, where the particle size of the atmospheric contaminants is larger than the wavelength of the laser light. The contribution of absorption by gas molecules and other particles to attenuation is most important in the infrared region of the spectrum. Atmospheric modeling software tools such as MODTRAN and FASCODE can be used to estimate atmospheric transmission properties.[23]

Notwithstanding this, while attenuation itself is not inherently probabilistic, the stochastic nature of meteorological conditions will mean that predictive models for atmospheric attenuation may be required to allow for the random variability associated with atmospheric conditions at any given time. Any model of these effects will need to include the location of the engagement (geographical and urban) and take seasonal and diurnal variations into consideration. If the relevant atmospheric parameters can be measured at the time of the engagement, then a more precise, real-time risk assessment would be possible.

2.1.3.2 Atmospheric Turbulence

Thermal effects can cause small but significant changes in the refractive index of the layer of the air close to the earth's surface. When convection currents and crosswinds break up this air, small regions of turbulence are formed which may act like lenses to focus or defocus a beam of radiation passing through them. For outdoor lasers where long beam paths exist, there is a possibility that this turbulence will cause fluctuations in irradiance, or hot spots within the beam with higher than average radiant exposure levels, albeit for short time durations. These fluctuations in beam intensity are commonly referred to as scintillations. The duration of the irradiance spikes is influenced by a wide range of factors, including cross-path wind speed and variability, beam divergence and focus, and the motion of the source and target through the atmosphere.

Atmospheric turbulence has the greatest effect at the ground surface. The degree of atmospheric turbulence is determined by the structural constant of atmospheric refractivity C_n^2, while C_n^2 changes at any time within a range from 5×10^{-8} $m^{-1/3}$ to 10^{-6} $m^{-1/3}$, basically related to the temperature gradient on the ground surface.[22] Turbulence reaches its highest value on sunny days when there is intensive solar radiation and surface heat rises, while on cold cloudy days, or at night, turbulence is weak. On windy days, when wind mixes the air, turbulent regions pass swiftly through the beam and cause associated fluctuations in energy distribution. The effects of turbulence become smaller at short distances and at greater heights above the ground surface.

2.1.4 Reflective Hazards

When the laser beam strikes the intended target some of the energy will be absorbed, while the remainder (neglecting transmission) will be reflected. The scope of

this report has been limited to exclude hazards from the direct beam, and, therefore, the only potential hazard to be considered is that from reflected radiation.

When the divergence and angle at which a reflected beam leaves a surface is the same as the divergence and angle at which the incident beam struck the surface, the refection is said to be specular. Mirrors and other shiny surfaces are examples of specular reflectors. Alternatively, when a laser beam strikes a rough surface, such as sand or dry earth, the reflected radiation tends to be scattered in many directions simultaneously, and this is called a diffuse reflection.

The nature of the reflecting surface affects the properties of the reflected radiation, but the precise three dimensional characteristics of the reflected radiation will depend on not only the reflecting surface, but also, particularly for specular reflections, the orientation of the reflecting surface with respect to the incident laser radiation, and the laser wavelength and polarization. It is likely that the radiation reflected from the target would have both diffuse and specular components, and consideration of both of these elements will be necessary.

2.2 Exposure Assessment

Given that the laser beam has struck the target and some of the radiation has been reflected down to earth, having been perturbed by the atmosphere throughout its passage, then consideration needs to be given as to whether this has actually resulted in human exposure, i.e. is there someone there? If this radiation falls to the ground without exposing anyone, then no hazard exists.

This element of the analysis will involve an evaluation of the local population distribution. The information required for this element might include:

- identification of relevant population centers in the direct and reflected areas of interest, and the calculation of population densities for urban, rural and sea areas, as appropriate;

- identification of population trends in the area (i.e. population variations with time);

- the location of any special areas of higher-than-average usage of magnifying optics around the area, together with the associated viewing characteristics;

- consideration of seasonal population changes; and

- identification of any significant transport routes in the area.

This analysis could be further refined to include behavioral characteristics, such as the likelihood that an individual is out-of-doors, and positioned such that the target tissue is exposed e.g. they are looking in a given direction. A worst-case assumption would be that both of these elements are true.

2.2.1 Personnel Protection Criteria

An important element in the probabilistic risk assessment is the biological damage model (or dose response curve). This describes the likelihood that someone will suffer harm, at the level of the personnel protection criterion, as a function of the level of exposure. In similar programs, for the evaluation of the risk of death from inert debris during space launches, a curve that relates the probability of fatality to debris impact kinetic energy (Figure 4) is used.[17] The curve is equivalent to the toxicity assessment in environmental remediation programs.[19]

Acceptable risk has historically been expressed using the terminology of "Expected Casualty" or "Probability of Casualty". The lower threshold for defining "casualty" can vary widely, and includes fatality. Fatality has previously been selected as the risk criterion (i.e. level of harm) for Test Ranges for the risk from inert debris mainly because other national standards use it and the definition is unambiguous.[15] However, since fatalities from laser exposure are unlikely, and significant injury can occur without fatality, the use of fatality would be inappropriate as the protection criterion for laser exposure, so another level of harm must be chosen. The form of the dose response curve will depend on the actual level of harm under consideration - clearly a function that defines the probability of a skin lesion will be different from that for a retinal lesion.
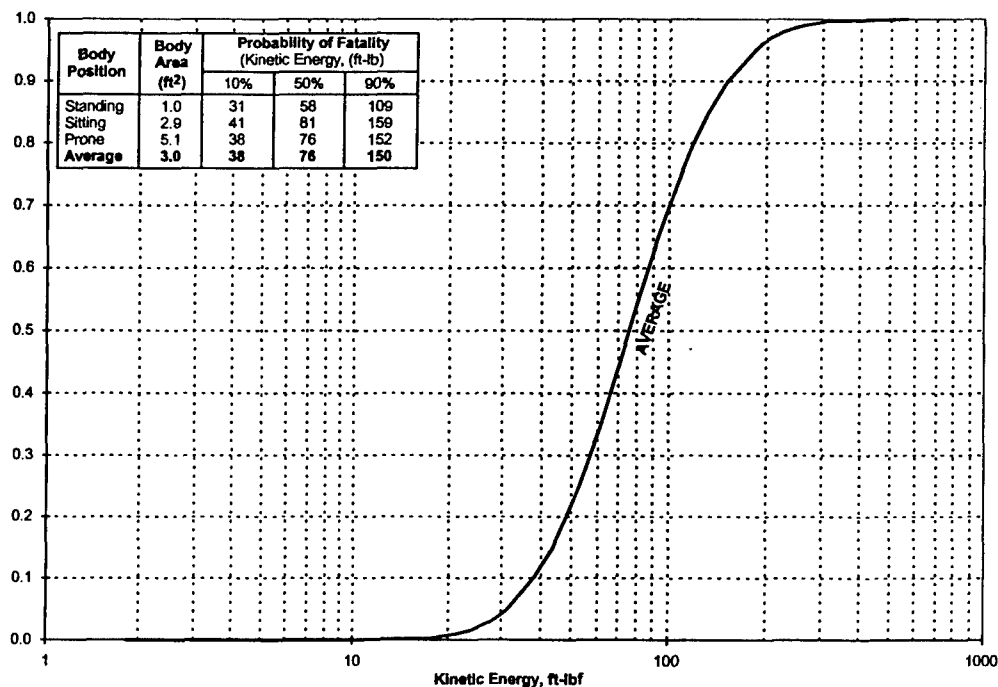

The embedded table reads:

Body Position	Body Area (ft²)	Probability of Fatality (Kinetic Energy, (ft-lb))		
		10%	50%	90%
Standing	1.0	31	58	109
Sitting	2.9	41	81	159
Prone	5.1	38	76	152
Average	3.0	38	76	150

Figure 4. Probability of fatality from debris impacts

Common risk criteria to protect personnel, aircraft, ships, and spacecraft from potentially lethal debris generated by flight tests and space launches have been developed and defined for the National test ranges.[15] A summary of the commonality criteria is given in Table 1. In establishing these common criteria, five separate types of logic were used, namely; consistency with prior safety criteria, legal considerations, similar

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regulatory experience (from local, state, federal, and international standards), comparable accident statistics, and correlation to the other criteria.

Table 1. Summary of commonality criteria for the National test ranges

Maximum Acceptable Probability	Undesired Event	Duration
1E-7	Individual Fatality (General Public)	One Mission
1E-6	Individual Fatality (General Public)	One Year
3E-5	Total Fatalities (General Public)	One Mission
1E-3*	Total Fatalities (General Public)	One Year
3E-6	Individual Fatality (Mission Essential)	One Mission
3E-5	Individual Fatality (Mission Essential)	One Year
3E-4*	Total Fatalities (Mission Essential)	One Mission
1E-2*	Total Fatalities (Mission Essential)	One Year
1E-7	Non-Mission Aircraft	One Mission
1E-6	Mission Essential Aircraft	One Mission
1E-6	Non-Mission Ships	One Mission
1E-5	Mission Essential Ships	One Mission
1E-7	Manned/ Mannable Spacecraft	One Revolution

*Advisory requirements

3   PROBABILISTIC LASER SAFETY

3.1   Probability Functions

A probability distribution is the set of outcomes of a random variable and their corresponding probabilities. Two commonly used functions to mathematically describe the probability distribution of a continuous random variable are the probability density function (PDF) and the cumulative distribution function (CDF). The PDF describes the probability of occurrences of particular outcomes. For example a PDF could be used to describe the range of weights in an adult population and their relative likelihood of occurrence (Figure 5). In this example the variable is normally distributed, although other distributions are possible. The CDF expresses the probability that the random variable assumes a value less than or equal to some value, i.e. it gives the cumulative probability of all outcomes at or below a specific value. For continuous random variables the cumulative distribution function is obtained from the probability density function by integration.

Graphs of PDFs and CDFs provide different, but equally important insights. A plot of a PDF shows possible values of a random variable on the horizontal axis, and their respective probabilities on the vertical axis. This plot is useful for displaying the shape of

the distribution, including the relative probabilities and most likely values. The CDF plot on the other hand is useful for showing fractiles (including the median), probability intervals (including confidence intervals), and stochastic dominance. Either function is a valid way of mathematically specifying the statistical distribution in probabilistic techniques. In Monte Carlo simulations, PDFs are used for specific input variables that are combined with point estimates to produce an output distribution for risk.

$$N(\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(X-\mu)^2}{2\sigma^2}} \qquad P_0 = \frac{1}{\sigma\sqrt{2\pi}} \int_0^{X_0} e^{-\frac{(X-\mu)^2}{2\sigma^2}} dx$$
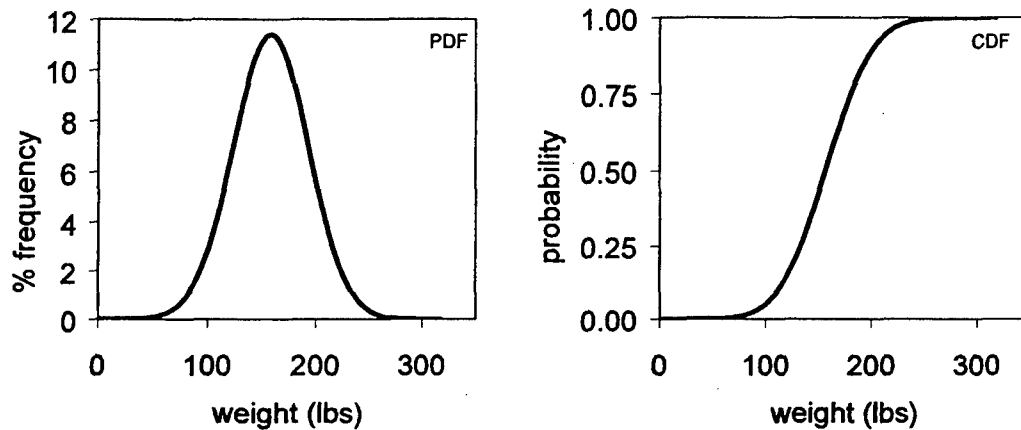
Figure 5. Probability density function and cumulative distribution function

Probability distributions can be assigned to data via graphical interpretation or formal statistical tests, and there are a variety of theoretical distributions used to represent populations and data sets. Use of these distributions is an appropriate way to represent the uncertainty and/or variability. The distributions most commonly seen in human health risk assessments are the normal, lognormal, triangular, beta, uniform, and empirical distributions.

Distributions can often be derived from data published in the literature; indeed these may have already been modeled and published with the data. Occasionally there will be "standard" distributions in the literature. Where there is a lack of knowledge two options are recommended. An informal approach to deriving a defensible distribution can be made based on an a priori knowledge of the nature of the stochastic (random) variable. The second method is a more formal approach to eliciting expert judgment to develop key parameters about which insufficient data are available as subjective PDFs. Processes for formal solicitation of expert judgment have been developed.[24]

In developing distributions for any specific element, the accuracy of the model needs to be studied. The significance and impact of inaccuracies should be analyzed using sensitivity analysis, and the need for using uncertainty propagation techniques (e.g. Monte-Carlo Simulation) considered.

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3.2   Probability Distribution Functions for High-Energy Laser Safety

As mentioned in the preceding section, many of the parameters that affect the likelihood and magnitude of irradiation of a given point in space, and the risk to human health are stochastic in nature and can be treated probabilistically, by assigning a probability distribution.

By defining density functions for all the elements that might lead to a risk of harm, multiplying all of these functions together, and integrating over all relevant ranges of associated parameters a probabilistic model can be developed. The number and nature of PDFs must be assessed on a case-by-case basis, as they clearly depend on the basic scenario under consideration, and the degree of complexity one wishes to apply. However, the basic framework remains the same as there is always an element that defines the expectation of harm, which in this case might be ocular, or skin damage, $E_{OD}(X)$ associated with some point X, due to accidental irradiation by laser energy[10]. The expectation can be derived from an equation of the following form:

$$E_{OD}(X) = P_I(X) \int_0^\infty P_S(g_s) P_{OD}(g_s H(X)) \, dg_s$$

where:

X	=	a general point on land, sea or air where someone might be exposed to laser radiation
$P_I(X)$	=	probability of irradiation of someone at a point X
$H(X)$	=	level of radiant exposure at a point X in the absence of atmospheric scintillation
$P_{OD}(g_s(H(X))$	=	probability of ocular damage if irradiated with energy of radiant exposure $g_s H$
g_s	=	gain in radiant exposure due to atmospheric scintillation
$P_S(g_s)$	=	probability density function for g_s

Referring to Figure 2, we can add the elements that need to be modeled to provide answers to those key questions for high energy laser systems[25]:
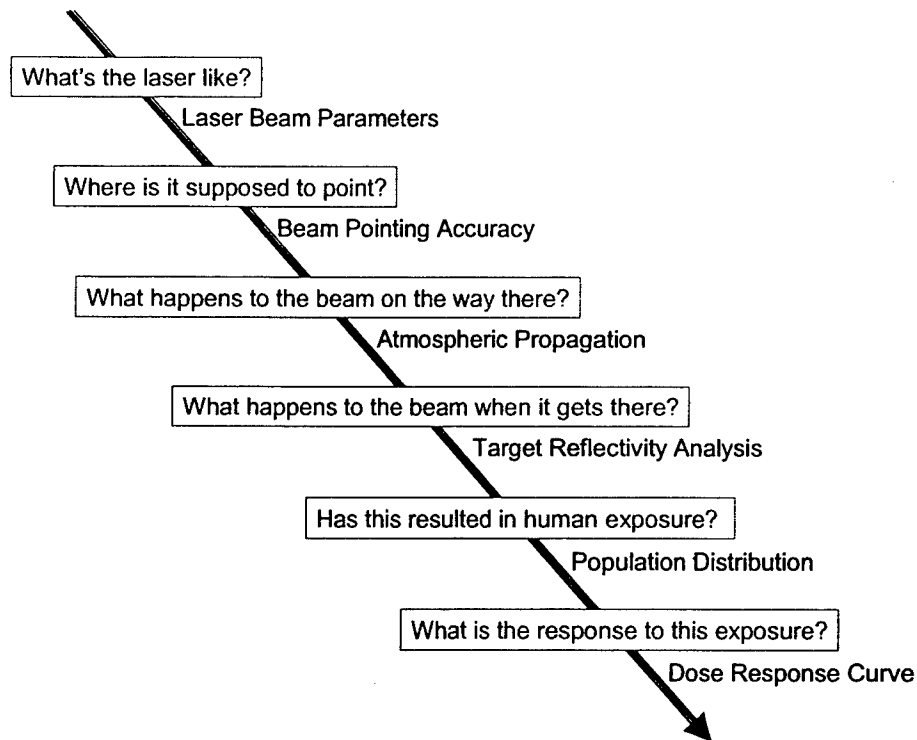
Figure 6. Principle elements of a HEL PRA model

3.2.1 Laser Beam Parameters

A variety of HEL laser applications, using different laser sources and optical systems, are proposed. The DoD currently funds three kinds of laser device technology for HEL weapons[26]: chemical, solid-state and free electron. Weapon class chemical lasers include hydrogen and deuterium fluoride (HF/DF, 2.55 - 4.0 µm) and chemical oxygen/iodine lasers (COIL, 1.315 µm). These devices have achieved megawatt-class power levels and simultaneous good beam quality. In the past, flashlamp-pumped solid-state lasers have produced high peak power, at the kilowatt level with good beam quality. However, it is the development of high efficiency, laser diode arrays in the mid infrared (IR) that enables the possibility of higher average power solid-state laser weapons. Free electron lasers have also produced kilowatt-class mid IR output with good beam quality.

Ideally, for each laser system under consideration, the laser output should be well characterized and its behavior understood. If this is not the case, then a worst-case estimate for parameters such as the beam power/energy, and beam divergence, should be used. A sensitivity analysis may be required to evaluate the effect of spatial beam distribution on the outcome of the risk assessment.

Laser system information generally required for the assessment include:

- the laser wavelength(s) in the laser system output,
- the maximum laser power/energy output from the laser system,
- the minimum 1/e point laser beam divergence,

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- the laser beam peak-to-average ratio,

- the laser beam diameter when output from the laser system,

- whether the laser beam is in the near-field or the far-field at the target location,

- the pulse width and maximum pulse repetition frequency of the laser system (pulsed lasers only),

- the energy distribution of the laser beam on emerging from the laser system, and

- how all these parameters could change over time.

It is also necessary to know of the existence of any secondary laser beams, or any other inadvertent laser energy leakage, emerging from the laser system, together with the above-noted characteristics of this inadvertent output.

3.2.2 Beam Pointing Accuracy and Failure Modes

Estimates for boresight errors, and tracking accuracy (jitter) are often combined to provide a single pointing parameter. This can be approximated by a radially symmetrical normal distribution with a mean aiming position and associated standard deviation (ref). For automatic tracking systems, as would be the case for HEL systems, as part of the system specification and testing, the manufacturer of the system would be expected to be able to provide this information.

Range safety requirements for the Eastern and Western ranges call for the submission of an analysis and supporting data outlining possible laser system failures for all phases of laser system uses [17]. The data is required in the form of the probability of occurrence versus time of operation for each of the following generic hazard modes (modes of beam control error or failure):

- pointing error,
- inadvertent slewing,
- premature firing,
- delayed firing,
- beam focusing error,
- loss of focus, and
- other modes such as wrong target acquisition applicable to the system.

If the probability of occurrence is non-zero for any of these hazard modes, then probability distributions for the random hazard mode parameters describing how each mode can occur over time must be provided.

The requirements also state that applicable hazard modes must be defined and documented by a failure modes, effects, and criticality analysis (FMECA) in accordance with MIL-STD-1543 and MIL-STD-1629 or the equivalent. The probabilities of

occurrence and the probability distributions of their descriptive parameters must be quantified with fault tree analyses or the equivalent. The level of analysis conducted in each case is the level at which appropriate component error/failure data are available. If necessary for confidence in the results, analyses of the effects of the uncertainties in the component data must be carried out.

This analysis and associated data would also be directly applicable to the full probabilistic analysis of the scenario under consideration, so this element should not place an additional data collection burden on the risk analysis.

3.2.3 Atmospheric Scintillation

The most advanced high-energy laser systems for engagements that include long, near horizontal propagation beam paths, will require adaptive optic systems. These systems are designed to compensate for atmospheric turbulence and distortion of the bean over long distances to ensure the maximum energy flux on the target. Adaptive optic systems include some form of wavefront sensor to measure the phase aberrations due to the turbulent atmosphere, and a deformable mirror to adjust the phase of the transmitted beam. In an ideal system the distribution of the compensated beam on the target will be gaussian, and will not vary in intensity due to atmospheric turbulence. However, even state-of-the-art adaptive optic systems will have limitations, so it is likely that some scintillation will remain. Also, the direct beam beyond the target, and any reflected radiation, will be subject to atmospheric turbulence, giving rise to scintillation, as it propagates away from the target.

3.2.3.1 Scintillation Model

The variation in energy due to scintillation is generally described in terms of a statistically varying multiplication factor, or gain, for the energy value detected behind an aperture due to scintillation. The probability that the scintillation gain (g_S) lies between (g_S, $g_S + dg_S$) can be approximated by:

$$p_s(g_s)d\lambda = \frac{1}{\sqrt{2\pi}}\frac{1}{g_s\eta}exp\left[-\frac{1}{2}\left(\frac{log_e\,g_s + \frac{1}{2}\eta^2}{\eta^2}\right)^2\right]dg_s$$

This is a log-normal probability function for the scintillation gain, and is equally applicable to both the spatial distribution of energy over the cross-section of any pulse, and the temporal (pulse-to-pulse) energy distribution along the beam path.[9] It is totally defined by one parameter, η – the standard deviation of the log-irradiance – that may be assigned any value appropriate to the degree of atmospheric turbulence to be expected. A complex relationship between the structural constant of atmospheric refractivity $C_N{}^2{}_n$ and η has been described.[27] Nonetheless, a worst-case value for η of 1.2 has been used previously, and this corresponds to severe turbulence levels as measured in Death Valley, Arizona. Measurements of air-to-air scintillation levels for the Airborne Laser

Experiment (ABLEX) in New Mexico and Montana[28] have determined levels of η of 0.638 over a 200 km beam path.

The ABLEX experiments refuted the popular notion that, from an optical turbulence point of view, the upper atmosphere is relatively stable at high altitude, since significant turbulence was detected, albeit not at the worst case level of η ($\eta = 1.2$) used elsewhere. The effect of reducing η from 1.2 to 0.638 can be seen in Figure 7, where the probability of getting a high level of gain (focusing) due to scintillation decreases with the reduction in η. For applications where adaptive optics are being used it may be possible to use the data from the instantaneous measurement of atmospheric propagation to provide an estimate of η for application to the reflected energy. If this is not available then a reasonable worst-case estimate would be required.
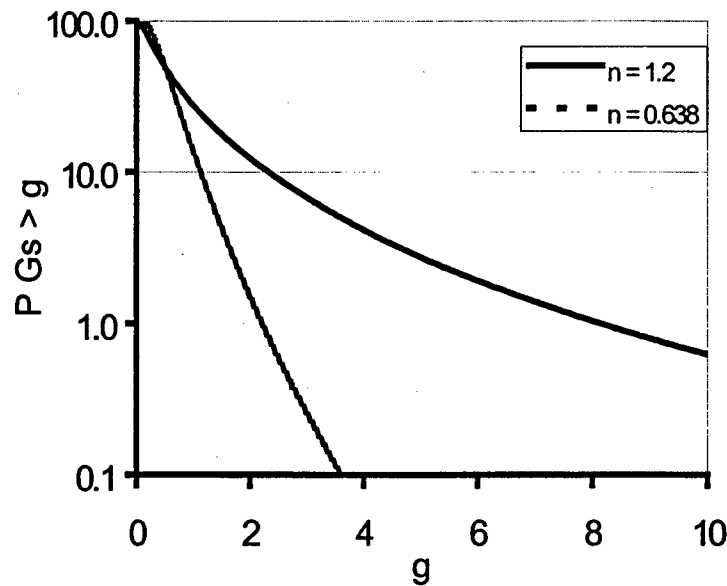

Figure 7. Probability (p G_s) that scintillation gain exceeds a given level (g)

The log-normal atmospheric model is presented by way of example. It should be noted however that there is large body of literature concerning the propagation of laser beams through the atmosphere. Many different statistical distributions have been fitted to the data, including the negative-exponential function (for super-strong scintillation)[29], a Rayleigh distribution (for very long propagation distances)[30], and the gamma-gamma PDF.[31] A more detailed discussion is beyond the scope of this report, but ultimately, as with all PFDs, the selection of a distribution will need to be fully explained and justified, with variability and uncertainty differentiated. Also, the numerical stability of the central tendency and the higher end (i.e., tail) of the output distribution should be discussed.

3.2.4   Target Reflectivity

Combining the laser to target geometry with a moving airborne laser source and a moving target, which has both specular and diffuse reflecting properties, will give rise to

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two main types of exposure scenarios at a given point on the ground. The specular component, may give rise to a short-lived, high-energy, specular reflection for a given point on the ground, while the diffuse component can result in a long-duration, low-power exposure. These dynamics, together with the atmospheric variations, will mean that it is necessary to calculate the time integrated intensity profile. This is because the biological response to the exposure is dependent not only on the laser power/energy, but also on the exposure duration and the rate at which energy was delivered to the tissue at risk.[22]

The target reflectivity model currently used for HEL safety assessments[1] is based on the bi-directional reflectivity distribution function (BRDF) developed by the Environmental Research Institute of Michigan.[32] The BRDF approach classifies the reflected energy into two regimes, diffuse and specular. The diffusely reflected radiation is spread into a full hemisphere, whereas specularly reflected radiation goes in a predominantly forward cone along the nominally forward direction.

It is thought that the BRDF model will overestimate the specularly reflected component and underestimate the diffusely reflected component, and this approach has been justified on the basis that is a worst-case scenario, consistent with safety.[33] However, this cannot be assumed. For instance, if there were a significant risk of over exposure to individuals from the diffusely reflected component, then any underestimation of this amount of radiation will potentially involve many more people than the specularly reflected component. This is because the diffusely reflected radiation is scattered over a larger area, resulting in potentially more people being exposed over longer exposure times. The specularly reflected component, on the other hand, will have a higher power, and is potentially more hazardous to an individual should it result in human exposure. A sensitivity analysis in the probabilistic risk assessment could be used to assess the relative contribution of each component to the overall risk assessment.

Furthermore, recent measurements and observations made during HEL laser firings indicate that both the surface geometry, and the surface reflection characteristics will not be static throughout the HEL engagement, but will change significantly as the paint and surface coatings burn off, and the constituent material deforms and melts. It is likely that the potential impact of time-varying target reflectivity and spatial redistribution of reflected light on laser hazard zones could only be accommodated in the hazard assessment using statistical techniques.

3.2.5 Population Density Modeling

Simplified models of population density have previously been developed by the Eastern and Western ranges to determine the likelihood of casualties if debris from space launches lands in a given region.[14] These models generally break the landmasses into regions in which the population is assumed to be equally distributed. Dense population centers and cities are separated from rural areas. Population data are reportedly available in the models for much of the world, although data for some regions, including Europe, are missing. Different population distributions and shelter probabilities are assigned

depending on the time of launch (day, evening, or night). For the risk from debris, shelter categories are defined as follows:

- Heavy - Blockhouse bunkers and heavily reinforced structures

- Medium - Buildings with concrete or reinforced roofs, and all floors except the top floor in multi-story buildings

- Light - Single story buildings, trailers, and top floors of multi-story buildings

- Exposed - No protection from falling debris

Similar categories could be developed for laser risks, for example heavy shelter could represent windowless buildings, medium shelter - internal rooms in windowed buildings, light shelter - external rooms in windowed buildings, and exposed - out of doors.

3.2.6 Biological Damage Model

In previous applications of probabilistic risk assessment to laser safety it has been stated that when considering the personnel protection criterion the level of harm should be small, but still capable of being easily detected. In addition, the consequent impairment to the individual should be minor, but not insignificant.[10] A significant level of harm is needed so that a meaningful level of "acceptable" risk level can be defined, for without harm there can be no risk. In contrast, risk assessments for other hazards (inert debris, blast, toxic effects) usually consider fatality as the personnel protection criterion. Since laser exposure can cause serious injury without fatality a non-fatal personnel protection criterion is required. However, if comparisons of the risk from laser exposure to other risks are to be made, attention should be drawn to the fact that the reflected laser risk from typical missile targets is a non-fatal one.

The proposed wavelength of some HEL systems is $1.315\mu m$[26], which is at the upper limit of ocular transmission, where there is still sufficient transmission through the ocular medium to affect the retina of the eye. However, a significant proportion of the incident laser radiation is absorbed throughout the ocular medium. In addition, that which does reach the retina is not focused to a minimal image size. This means that a very high level of radiation must be incident at the cornea before detectable funduscopic damage to the retina is apparent.[34] The nature of a lesion from laser radiation in this wavelength region is different from a lesion from a visible laser exposure, with a significantly greater volume of retinal tissue being involved with the former. Also, the usual definition of a minimal lesion detectable by funduscopic examination may not be appropriate since other techniques (e.g. scanning laser ophthalmoscopy) may detect a lesion at significantly lower exposure doses. A "threshold" lesion in this case, i.e. one that is detectable by funduscopic examination, may, therefore, represent a lesion that would have potentially significant and long lasting impact on visual function.

Ongoing studies in AFRL/HEDO are in place to experimentally determine the ocular damage thresholds for pulsed and continuous wave lasers operating at around $1.31\,\mu m$. Two exposure scenarios are being examined. The first scenario represents an exposure that could be encountered in a battlefield (or training) environment where both the laser source and the target are moving and the eye receives a momentary direct

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illumination, or a glancing specular reflection. In this case the dwell time of the laser beam in intercepting the eye will be short, and an exposure duration in the order of a fraction of a millisecond has been chosen as representative for this scenario. The second exposure scenario assumes that the observer is exposed to a relatively low-level reflected laser exposure, most likely from a diffuse reflection. Since there will be no visual cues the observer may not exhibit an aversion response or otherwise take evasive action. In this case, a "worst-case" continuous wave exposure duration of up to 10-sec is being investigated. This duration is also defined by current safety standards for invisible laser beams.

However, for some of the longer wavelength systems the cornea or skin may be the more vulnerable tissue. Studies will be needed to determine the tissue at risk. Furthermore, for long duration, low level exposure to long wavelength infra red radiation, where injury will arise through thermal mechanisms, it may be that there will be some sort of aversion response before any permanent tissue damage occurs. Such a human response can be embraced by the safety assessment, by limiting the duration of the exposure, if data on the latency of the response can be provided.

For any study of laser induced ocular damage the results are usually expressed as a dose-response curve relating the exposure energy to the frequency of detected lesions. A typical dose-response curve is shown in Figure 8, together with the cardinal point known as the ED_{50}, which is the median dose, required to produce a lesion in 50% of the cases, and generally referred to as the "damage threshold'. The data can be fitted well with a cumulative log-normal frequency distribution, and probit analysis[35] is often used to fit the data in the form of a straight line relating the probit value[c] to the dose (Figure 9).

Previous applications of probabilistic risk assessment have used the complete probability curve that relates the probit values, and hence lesion probability, to the dose.[36,37] For the application of the dose-response data in a probabilistic risk assessment it is therefore important that studies of biological damage thresholds provide the full dose-response curve. This is usually given by reporting the ED_{50}, and the slope, of the probit line. This curve can then be used to calculate a value for the probability of injury for a given dose. In doing so, as the ocular injury function is followed down to low exposure levels, a corresponding theoretical probability of injury would be predicted, albeit small. However, on biophysical grounds it can be argued that, for exposures in the normal physiological range, the probability for injury must be zero and the function should be truncated, and reduced to zero probability at low exposure levels.

The question of whether a process has a threshold is fundamental to quantitative and qualitative risk analysis.[16] However, a prohibitively large number of exposures would be needed to accurately determine the risk at low exposure levels, and thus identify this cut-off level. An argument could be made for truncating at the level of the

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[c] Probit values are simply probabilities on a transformed scale. For any P, the probit value is the normal equivalent deviate increased by 5, thus a probit value of 5 corresponds to $P = 0.5$.

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MPE, this being defined as a safe exposure level. An important observation is that the use of a function that is not truncated will overstate the risk at low exposure levels, and err on the side of caution.
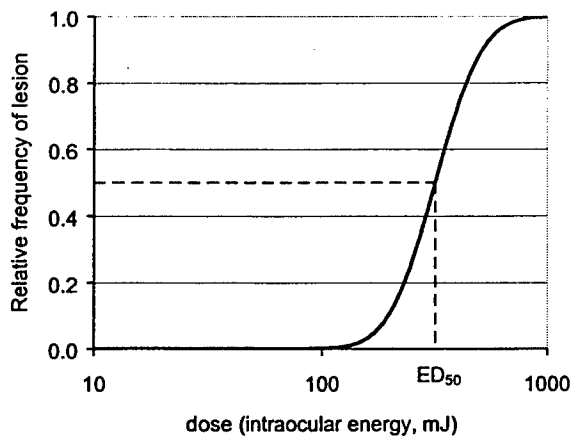

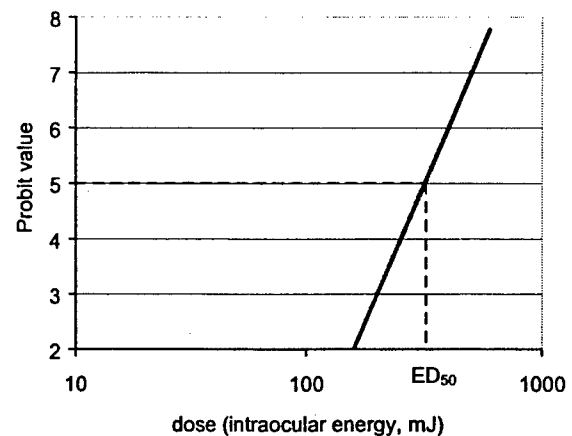Figure 8. Typical dose-response curve for laser-induced ocular damage

Figure 9. Probit transformation of the dose-response curve for laser-induced ocular damage

It may also be important to consider experimental bias and the uncertainty of the ED_{50} value and slope of the dose-response (probit) curve in a probabilistic analysis. The possible contribution of experimental bias to the ED_{50} and the slope has previously been analyzed, and a probabilistic risk assessment model for low-power space based lasers (e.g. lidars) accounting for uncertainty associated with the parameters of the ocular damage model has been developed[37]. Probability distributions, modeling both the biological variability of laser bioeffects on tissue and the uncertainty associated with the variability can be carried through a second order model with a Monte Carlo approach.

4   DISCUSSION

Deterministic laser safety calculation techniques, as employed by the USAF's Laser Range Safety Tool[1], are completely appropriate for test ranges and flight tests. However, as HELs move out of test ranges and into operational modes, the number of effective control measures diminishes, and deterministic hazard zones may be overly conservative[38]. In the extreme, on the battlefield it will be necessary to deconflict the risk from the laser energy with other resources in the battle space, and commanders will need to make informed decisions about the potential for fratricide and collateral damage, including laser injuries.

Sophisticated probabilistic risk assessment models can be used to provide decision makers with more complete information to be able to assess the risk from the use of HELs in outdoor environments, especially where the source and/or target are moving. These models can be used to estimate the risk from reflected radiation of the proposed lasing scenario to human health, and this information can guide laser safety

officers, range safety managers, and military commanders in making risk management decisions.

Models of probabilistic risk assessment can only be of value if an agency is empowered to ultimately accept the hazard or risk. In the USAF, common risk criteria have been developed and accepted for the Eastern and Western ranges[17], and the National test ranges.[15] Common criteria are defined for the risk of fatality from space and missile launches, and the risk to both domestic and foreign populations is considered. The general philosophy of the application of risk assessment techniques to support military systems, together with the existence of common criteria are of value to the HEL PRA program as they indicate that the approach has been studied in detail, and accepted, by the Range Commanders Council. It is therefore unlikely that a fully justified and documented probabilistic risk assessment model for high-energy laser safety would be rejected.

Like probabilistic risk assessment models developed to support space launches, those supporting high-energy laser safety applications are likely to be complex. Even when a core generic model can be developed, additional system and scenario specific data is likely to be required to support a particular application. Although much of this will be required in the form of point estimates for a deterministic hazard assessment, the additional information required to develop a PDF may be more difficult to obtain, and any PDF used in the assessment will require additional justification and documentation.[13] Some of these PDFs may be generic to any laser safety scenario (e.g. atmospheric propagation), others may be specific to the laser and system under consideration (e.g. aiming accuracy and fault modes).

Decisions regarding the allocation of future resources to attempt to reduce the lack-of-knowledge, and gather new data, should take into consideration the most influential input factors in the model and the cost of gaining new information about these factors. Sensitivity analysis can be used to identify which factors are most important in the model. Once so determined, the source of its spread or distribution should be determined. If it has a significant uncertainty component, further research can be used to reduce this uncertainty. If, on the other hand, the distribution represents inherent variability, the spread cannot be reduced.

The intention of this report is to provide a detailed overview of the potential applicability of the probabilistic risk assessment to support the use of high energy lasers by the USAF, the processes involved in a probabilistic risk assessment as applied to laser safety, and summary details of the information required for probabilistic risk assessment model development and application. An indication of the main exposure pathways, and principal elements requiring modeling through the development of probability distribution functions has been provided. It is suggested that a detailed study of the requirements for each specific distribution function be carried out, and documented in a series of subsequent reports, where the process of selection of the particular function can be explained and fully justified.

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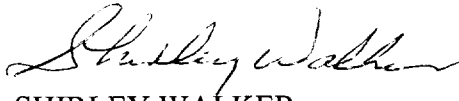
16 May 2002

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The attached copies of AFRL-HE-BR-TR-2001-0170 are corrected copies of our earlier submission. The changes are:

Last word on cover has been changed from ENERGY to SAFETY

Page 21, paragraph 3.2.6, line 14, reference to Table 2 has been deleted.

If you have any questions, please call.

SHIRLEY WALKER
STINFO Officer
AFRL/HEOA
2509 Kennedy Circle
Brooks AFB 78235-5118
e-mail: shirley.walker@brooks.af.mil